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Model predictive control of a free piston compressor/expander with an integrated linear motor/alternator

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Abstract. Linear positive displacement machines are becoming increasingly more attractive for applications that are normally known as unconquerable niches of rotary and scroll machines. Free-piston machines are characterized by the absence of a crank mechanism, since there is a direct transformation of electrical energy into the piston movement. From the point of view of manufacturing, these machines benefit from a higher robustness and reliability because of less mechanical components involved and reduced frictional losses associate with a conventional crank mechanism.

However, the major challenge in replacing the rotary machines by linear ones is a lower efficiency at lower speeds which is unavoidable because of the nature of linear motion: continuous operation means a reciprocating movement within a stroke length with significantly long periods of acceleration and deceleration when the speed is far from its optimal value. However, the advantage of free-piston machines is the fact that the motion profile is freely configurable within physical constraints, which provides a possibility to optimize the speed given the efficiency map of particular linear motor.

While the methods and results of the efficiency assessment for rotary machines are widely available, there is a lack of these analyses for linear machines. The current study provides in-depth analyses of a double-coil iron core linear motor also acting as a generator.

1. Introduction

Linear drive systems are widely used in industry, for instance, in various pick-and-place applications, computer numerical control (CNC) machines among others. Where a linear motion is involved, such machines and actuators provide the possibility of direct transformation of electrical energy into the required motion profile. If a rotating machine is used, the rotation needs to be transformed into translation by means of diverse transmissions such as crank, screw, swash plate, rack, and pinion mechanisms. Mechanical losses, associated with the transmission, affect the overall efficiency of the system. If a linear motor is implemented, an improvement of around 5.5 % can be obtained, as reported by [1]. However, the efficiency of linear motors is



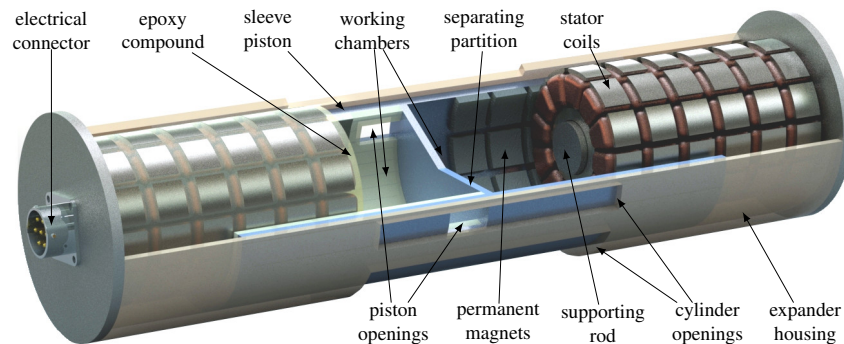


Figure 1. The concept of a new expander/compressor.

in general lower than this of rotating machines [2]. If a reciprocating machine is driven with a linear motor, there are two important aspects to be discussed:

- variable and alternating force originating from the compression or expansion profile;
- motor/drive efficiency at speeds varying from zero to maximum.

In this work, a volumetric machine is considered to be reversible and acting either as a compressor or an expander (CE). A linear electric machine can also operate in both the motor and alternator mode and called a linear motor/alternator (LMA).

In the case of a rotary compressor or expander, the flywheel or the rotor of the motor/alternator compensates torque pulsations introduced by CE. Hence, the motor can operate at almost constant design point. The reciprocating piston motion is realized by means of a crankshaft mechanism allowing the motor to rotate always in the same direction at a constant speed. These are great advantages of a rotary system in respect to a linear one. Because of a limited stroke length, a linear motor needs to accelerate and decelerate continuously, so a significant part of the time if the speed of the mover is non-optimal. Due to the operation mode, there is an altering energy flow from and back to the grid. If a free-piston compressor operates connected to the grid, the latter plays the role of a flywheel being able to provide and to absorb electric energy. If such a machine operates in island mode, there are two strategies possible:

- the motor accelerates the piston, the piston is stopped by the gas and frictional forces only. In this case, the injection of electrical energy into the grid can be avoided;
- if the previous profile appears to be non-optimal, the motor can operate also in alternator mode, absorbing excessive kinetic energy of the piston. In this case, the absorbed energy must be either injected into the grid or stored in order to be used in the next reciprocating cycle. Super capacitors or a battery storage can be considered for this purpose.

This study continues the previously developed model of a free-piston linear compressor/expander described in [3]. The conceptual design is depicted in Figure 1. Two working chambers are formed by the LMA stators and the sleeve piston. The piston has two degrees of freedom: the linear motion is used to compress or expand the working fluid, the rotation closes or opens the ports independent of the piston linear position. The latter is realized by aligning the piston openings with the housing openings. A smaller opening shown on the front side is connected to the high pressure line. A larger opening at the bottom of the unit is connected to the low pressure line. When the left working chamber is connected to one of the external lines and the piston moves towards its left dead point (LDP), the working fluid is discharged into the line connected. The intake process occurs if the piston moves away from the LDP. If the openings are closed, the working fluid is isolated from the external lines and can be compressed or expanded. The right working chamber operates in the same way.

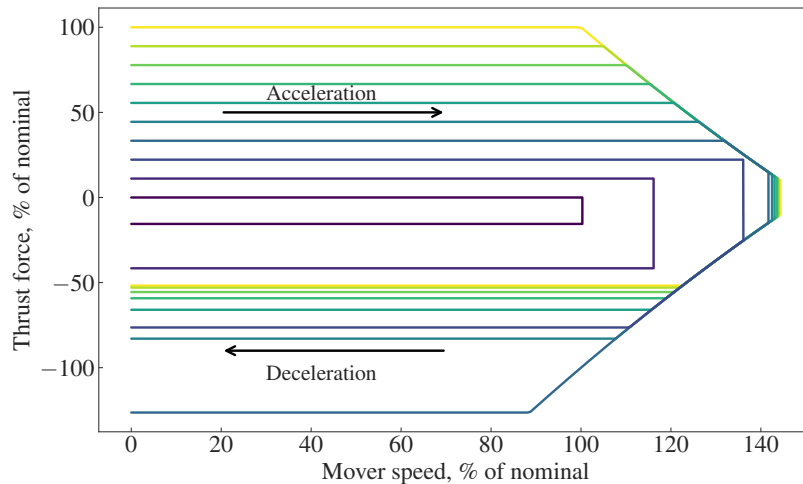


Figure 2. Thrust force profiles as a function of the mover speed

The operation mode can be switched from compressor to expander and back by altering the rotation direction of the piston, and therefore, by reversing the port opening sequence. The function of the in- and the outlet ports are also altered.

The LMA of the proposed device comprises two independent permanent magnet synchronous motor (PMSM) units which stators are placed inside of two opposite working chambers and acting in parallel. Permanent magnets are attached to the inner wall of the piston. During its operation, the piston continuously accelerates and decelerates by means of LMA. The same motors rotate the piston opening and closing the in-and outlet ports.

2. Simulation of the piston motion

Based on the comprehensive mechanical model described in [4], including predicted gas and frictional forces, several piston movement profiles have been built and analyzed as it is shown in Figure 2. As a starting point of these simulations, a minimal electromagnetic force is calculated, which is needed to initiate the piston movement while there is no pressure difference across the separating partition. The piston must stop at the end of the stroke by means of the gas and the friction force only. Every next step, the electromagnetic force is been increased by 10 % of the nominal one. In order to stop the piston, an additional reversed force must be applied. When the maximum speed or a critical piston position has been reached, the piston has been decelerated by the same motor acting as an alternator. The critical position is the piston displacement at which the piston still can be stopped by means of the acting forces before it reaches the dead point. The required brake force can be found iteratively. For each value of the accelerating thrust force, a work consumed during one acceleration/deceleration cycle is calculated and the maximum is found. This technique does not include the LMA efficiency at this point, therefore the obtained movement profile is only optimal from a thermodynamic point of view.

3. Experimental setup

In order to design and to validate models needed for the control system development, an experimental setup has been built as described in [7]. The linear motion is separated from rotational motion in order to facilitate the study of both. The translation of the piston is realized by a linear motor/alternator (LMA). This device is assembled from standard industrial components in a custom-designed housing containing a linear guiding system. The LMA

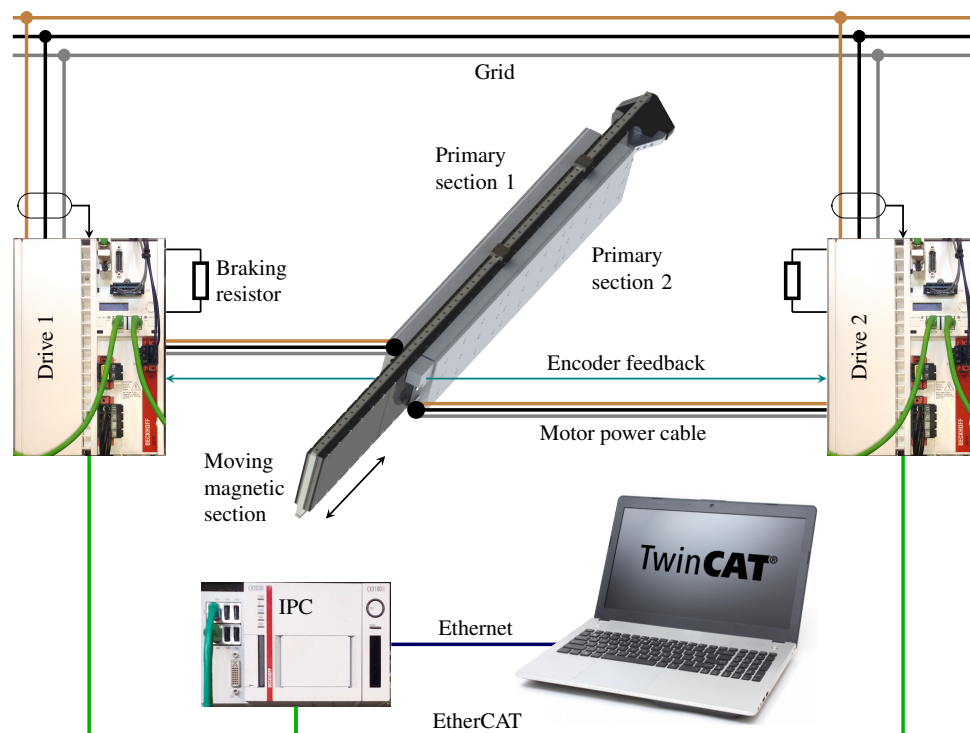


Figure 3. Test setup configuration; the linear motor is shown without the housing.

comprises two iron core coils placed opposite to each other. The three-phase windings share the same laminated iron core. A sliding frame with back-to-back attached magnetic sections is supported by linear bearings. The permanent magnets are attached to the back plates with a step of 0.012 m and skewed with the angle of 88 degree. The mover is connected to the compressor through a rotary bearing which decouples the rotation of the piston shaft. This connection is rigid since it contains no elastic parts.

Both motors are connected to their own drives as it is illustrated in Figure 3. Each motor is provided with its own incremental magnetic encoder. Magnetic encoders are highly immune to contamination in an industrial environment. Therefore, electromagnetic encoders provide very robust measurements. However, special attention is needed when incremental encoders are used. For instance, the position reading is only certain within a magnet pitch but not within the full stroke length. Therefore, zeroing is required after a signal interruption due to i.e. a power failure or at the start up. This procedure is realized by slowly moving the piston until its extreme position and detecting the rising current when the piston is stopped.

The hardware is controlled by TwinCAT 3.1¹ programming environment installed on an industrial personal computer (IPC). The data is transmitted between the drives and IPC through EtherCat fieldbus system based on Ethernet network. This configuration is designed for real time computing, required for dynamic applications such as the current one.

4. Description of the experiments

The fact that LMA is built from two independent motors sharing the same moving magnetic section, provides a natural possibility to investigate the efficiency of the motors without any additional equipment. The motor being tested must be configured to follow a reciprocating

¹ <https://www.beckhoff.com/english.asp?twincat/twincat-3.htm>

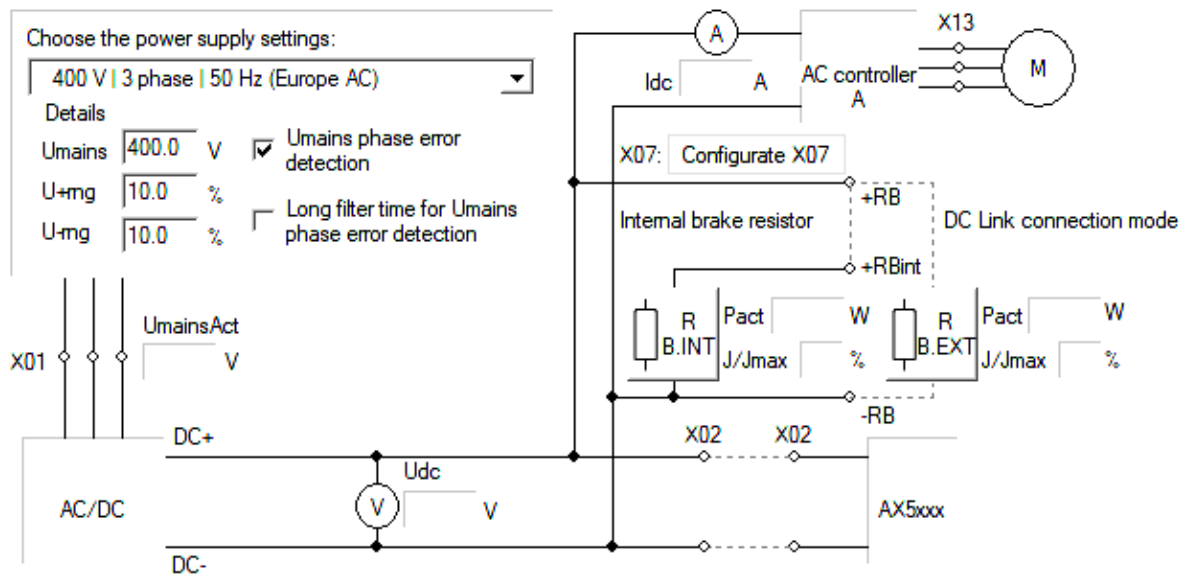


Figure 4. Screenshot of the DC current and voltage measurement points configured in TwinCAT. Source: www.beckhoff.com

profile with a certain constant speed part of the trajectory. The second one must provide a constant force independently of the first motor behavior. The unit being tested must overcome the load if the braking force is oriented against the movement direction, acting as a motor. During the returning part of the stroke, this unit acts as an alternator dissipating the produced electricity as heat in braking resistors. Therefore, one motor can be tested as well in motor as in alternator mode during one reciprocation cycle.

The LMA efficiency map can be found experimentally by means of an adjusted method described in [5, 6] for rotating machines. By varying the load and the speed values from zero to a maximum, the efficiency map for whole operation range can be obtained. Since both motors are connected and configured in the same way, both can be tested just by altering the configuration in the software of the setup.

The work of the inertia force is assumed to be zero as the initial and final piston velocities are also zero. The source of losses is the frictional force and the alternator losses. The frictional force is included into the model and therefore can be taken into account. The efficiency of the piston motion η_{el} is the ratio of the work produced by the section acting as an alternator and the work consumed by the section acting as a motor. The resulting efficiency is the product of the efficiencies of both sections. The electrical efficiency of one section can be approximated as a square root of the total efficiency as follows:

$$\eta_{el} = \sqrt{\frac{\int_0^L U_{dc,mot} I_{dc,mot} \cdot x dx}{\int_0^L U_{dc,alt} I_{dc,alt} \cdot x dx}}, \quad (1)$$

where U_{dc} is the voltage and I_{dc} is the current measured at the direct current (DC) bus of the drive as it is shown in Figure 4. Subscripts *mot* and *alt* mean the parameters of the motor and alternator respectively. L is the stroke length.

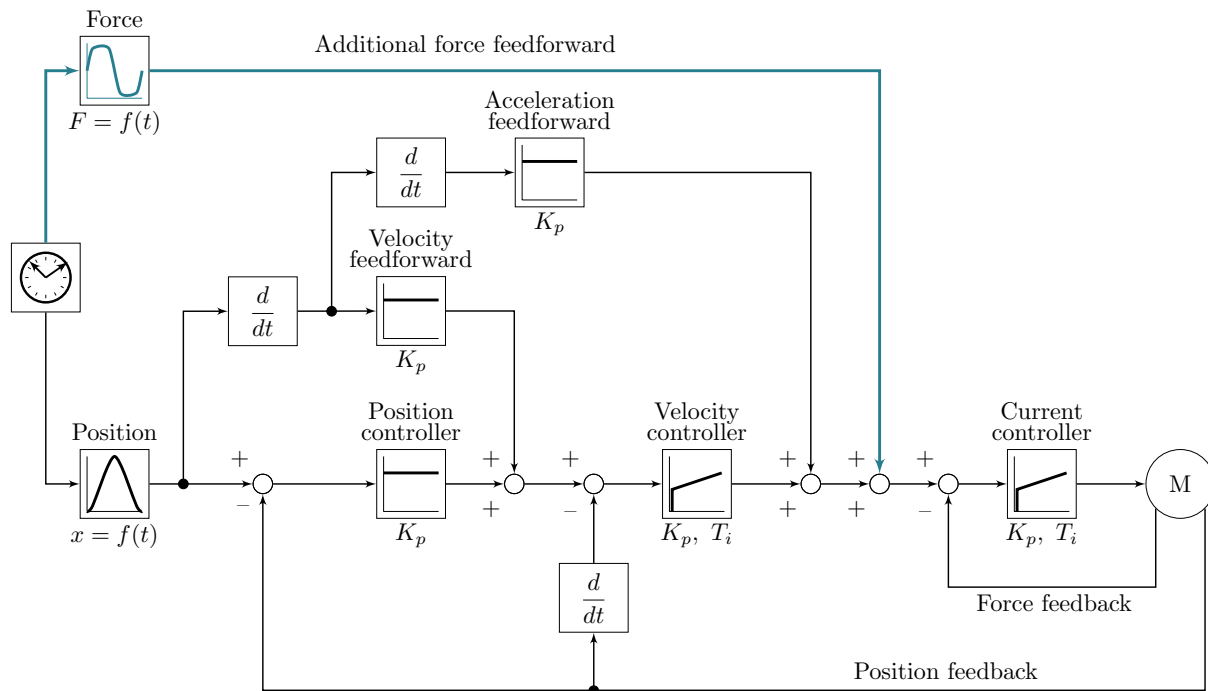


Figure 5. Positioning error with and without feedforward.

5. Improvement of the control algorithm

The standard PI control algorithm implemented in the current setup shows adequate performance, however, the positioning accuracy must be improved in order to measure the motor efficiency or to realize the right port timing. Overshoots must be avoided as these lead to a mechanical damage in a real installation. The developed mechanistic model can be used to generate a force feedforward action for the controller as it is shown in Figure 5.

In the following experiments, a triangular piston movement profile was used as input. The goal was to accelerate and decelerate the piston as fast as possible in order to achieve a constant speed during a relatively long period of time. Based on this profile and the expected forces acting on the piston, the thrust force which must be delivered by the LMA, was simulated. Further, this force profile was linked to the LMA controller as feedforward action.

6. Results and discussion

The main goal of this study is to formulate a method for matching of an optimal compression/expansion profile with the maximum efficiency profile of the motor/alternator.

The compressor/expander model is used in order to simulate an optimal piston motion profile. As it can be seen in Figure 6, the acceleration force for the current setup should not exceed 35 % of the rated force and the braking force should be in the range of 40–50 %. This operation mode minimizes the frictional and alternator losses and improves the power output or consumption.

The same model is used in order to improve the controller performance. The implementation of the new control algorithm results in more constant and predictable force profiles. This allows to map the cogging force and to compensate it by adding this force to the feedforward action. The cogging force was estimated as it is shown in Figure 7. The obtained array of values, linked to a piston position, was included into the model. After the feedforward (FF) action has been applied, the piston speed and the thrust force depicted in Figure 8 and Figure 9 respectively have become more stable which is important for the efficiency assessment.

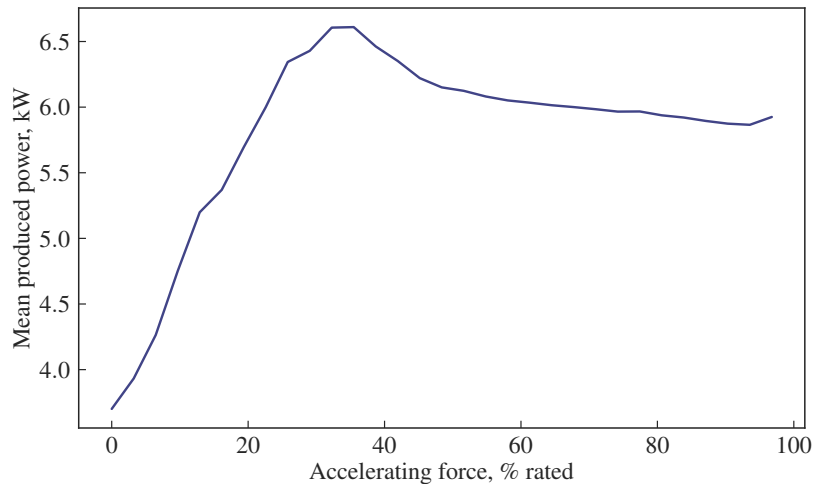


Figure 6. Mean net power produced at different accelerating forces.

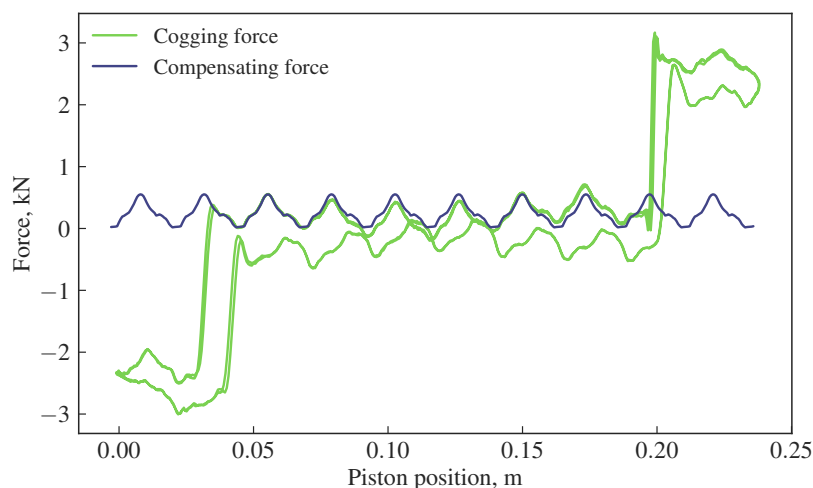


Figure 7. Captured cogging force.

Figure 10 shows the result of four runs with PI controller only, with the injection of the feedforward action, and both with a compensation of the cogging force during the piston backward motion. As it can be seen, the positioning in the vicinity of the dead points is significantly improved from about 4 mm in the reference case to less than 1 mm with feedforward. Ripples from uncompensated cogging force are still present, however, an improvement in respect to the case without cogging compensation can be clearly seen.

In order to estimate the efficiency of the LMA, one full reciprocating cycle is used: (i) the mover is accelerated until the target speed is reached, then it is decelerated and reversed at the other dead point. The load is applied by the slave section. (ii) The mover travels in the same way back, the direction of the load force remains unchanged.

The LMA efficiency map is depicted in Figure 11. The efficiency is maximal when the mover speed and the maximum thrust force are around 50 % and 35 % respectively of the rated parameters. These results are in a good agreement with the expander optimum speed depicted

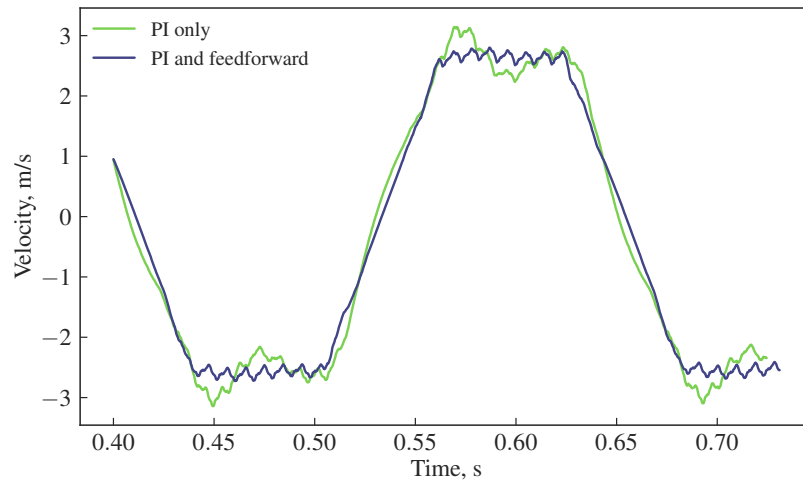


Figure 8. Speed profile with and without feedforward.

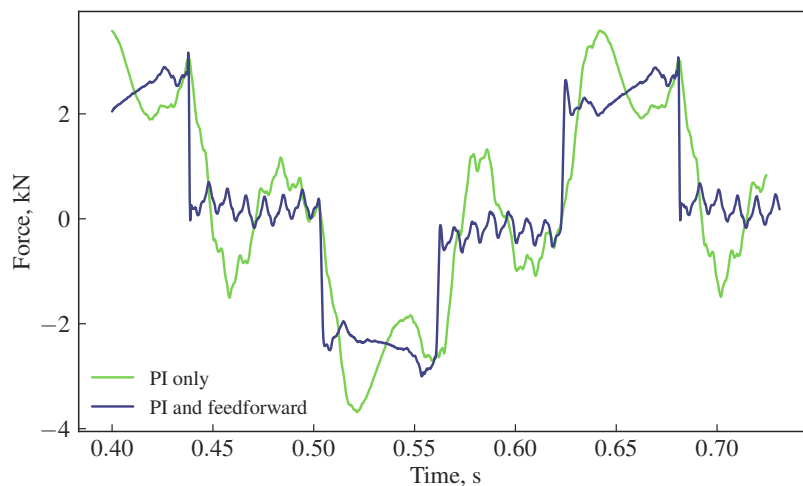


Figure 9. Thrust force profile with and without feedforward.

in Figure 6.

7. Conclusions

The forces acting on the piston, especially, the frictional and the cogging one have a complex behavior and are difficult to formalize for control purposes. These forces can be included into the model by means of experiments. The obtained simplified model provides a feedforward signal for the motor controller. This approach allows to improve the piston positioning in high-dynamic applications.

The iso efficiency map of the linear motor/alternator is estimated experimentally by applying a continuous motion profile with a constant speed part. By measuring the power consumed by the accelerating section and the power generated by the braking section, the total efficiency of the motor train can be estimated.

The proposed method uses embedded sensors which are characterized by a lower accuracy in

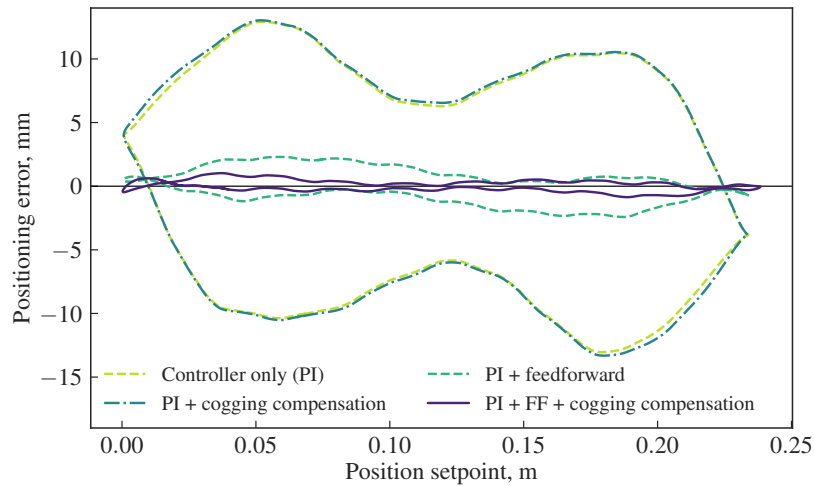


Figure 10. Positioning error with and without feedforward.

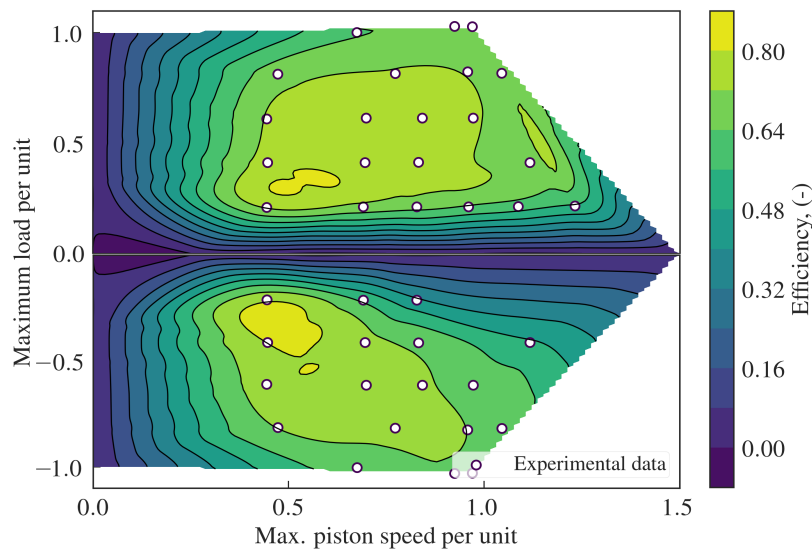


Figure 11. Efficiency contour for one motor/alternator section.

respect to specialized measuring devices. It was not possible to obtain the exact value of the error from the manufacturer. Therefore, an in-depth discussion about the accuracy is skipped. The estimated error is not larger than 3–5 % but this value is obviously uncertain. The absolute values of the efficiency are not of a great importance for the current study. The goal is to define a motion profile with the maximum efficiency, shown in Figure 11. The obtained efficiency map allows to match the movement profiles with the maximum electrical and thermodynamic efficiency. By combining theoretical study of the piston motion with experiments, the maximum overall efficiency for the given mass flow rate and pressures can be assessed.

Nomenclature**Acronyms**

CE	Compressor/expander
DAQ	Data Acquisition
FF	Feedforward
HDV	Computer numerical control
IPC	Industrial Personal Computer
LDP	Left Dead Point
LMA	Linear Motor/alternator
MPC	Model Predictive Control
PI	Proportional-integral
PMSM	Permanent Magnet Synchronous Motor
RDP	Right Dead Point

Greek Symbols

η	Efficiency	—
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Subscripts

<i>alt</i>	Alternator
<i>dc</i>	Direct current
<i>el</i>	Electric
<i>mot</i>	Motor

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